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Experimental Investigations on Pocket Milling of Titanium Alloy Using Abrasive Water Jet Machining

Abrasive Water Jet Machining (AWJM) is one of the most popular unconventional machining processes used to machine difficult-to-machine materials. Apart from regular cutting, it is also used for turning, threading, slotting, milling, etc. This paper details the experimental investigations on Abrasive Water Jet Pocket Milling (AWJPM) on Titanium (Ti6Al4V) using garnet abrasive. The influence of waterjet pressure, step-over, traverse rate and abrasive mass flow rate were studied on the output responses such as depth of cut and surface roughness (Ra). The experiments were designed using L9 Orthogonal Array and ANOVA analysis helped in determination of significant process. ANOVA analysis on depth of cut indicated that step-over and traverse rate are the most significant process parameters. However, ANOVA analysis for surface roughness (Ra) was inconclusive and the significant process parameters could not be determined.

Keywords: *hydraulic turbine, on-cam characteristics, neural network*

1. INTRODUCTION

Recently, Abrasive Water Jet Machining (AWJM) has received considerable attention from industries owing to its beneficial characteristics in machining various materials, particularly difficult-to-machine and thermally sensitive materials [2]. AWJM uses the mechanical energy of the high velocity jet of water and abrasive to achieve material removal by impact erosion. Besides cutting, many operations such as turning, threading, slotting and milling can be performed using AWJM. There has been a certain degree of research in the fields of slotting, turning using AWJM, but the studies related to milling using AWJM is very scarce [3]. If the depth of cut is controlled during the milling process, then it is known as pocket milling. In abrasive water jet pocket milling (AWJPM), the waterjet is not allowed to pass all the way through the workpiece. The advantages of AWJPM are less burr information, minium thermal distortion, negligible tool wear, absence of tool breakage and tool deflection [2-9].

The process parameters in AWJPM are broadly classified into six categories namely (1) Hydraulic parameters: waterjet pressure, orifice diameter and water flow rate (2) Mixing chamber and acceleration parameters: focus nozzle diameter and focus nozzle length. (3) Cutting parameters: traverse rate, number of passes, stand-off distance and impact angle (4) Abrasive parameters: abrasive flow rate, abrasive particles diameter, abrasive size distribution, abrasive particle shape and abrasive particle hardness (5) Work material: composition, hardness and harder materials (6) Milling parameters: Step-over size, number of passes and nozzle path movement (Figure 1). The influence of these parameters on the output responses have to be studied for titanium alloy.

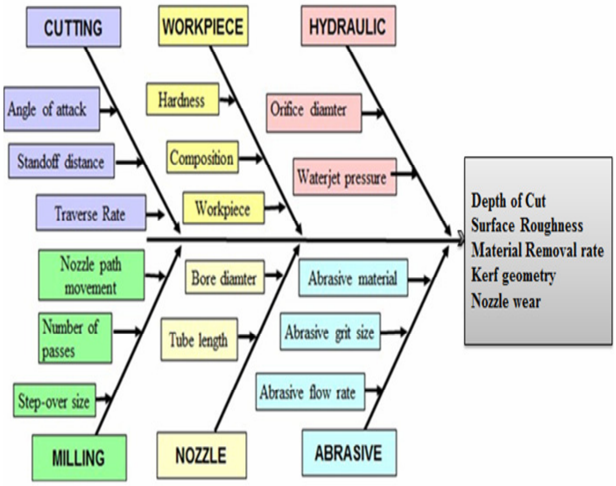

Figure 1. Fishbone diagram for AWJPM

2. LITERATURE REVIEW

Hashish (1998) developed isogrid patterns in aluminium and titanium using AWJPM to increase the strength of the materials. Applications of isogrid structures were extremely useful in the field of aerodynamics. He observed that factors like degree of overlap, cross feed increment and mixing tube diameter are significant for the formation of the required patterns.

Shipway et al (2005) studied the surface characteristics of AWJPM on titanium alloy (Ti6A14V). They observed that the material removal rate is about 55 % lower at higher traverse speeds (0.01 m/s) with

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smaller grit size (80 mesh) than that of with the larger grit size (200 mesh). They have also observed that increase in traverse rate results in the reduction in surface waviness, while using both grit sizes of abrasives (garnets). The reduction is being most significant while using larger grit size of the abrasives. They have also observed that the material removal rate was high at the lowest traverse rate (0.003 m/s) and decreased rapidly with increased traverse rate. From their studies, it is observed that increase in the water jet pressure for different traverse rate results in an increase in the surface waviness and also the water jet pressure has significant influence on the surface waviness at the lower traverse rate than that of the higher traverse rate. They have also studied the effect of jet impingement angle (angle of impact of the jet on the workpiece surface) on the material removal rate. They found that the material removal rate was low with low impingement angle (15˚) and it increases with the increase in the impingement angle (60˚). However, the material removal rate decreases as the impingement angle moves towards the normal (90˚). They observed that the surface waviness and surface roughness significantly change proportionally with the impingement angle while using both the grit sizes. They have also observed that the surface roughness decreased as the impingement angle decreases for both grit sizes (mesh 80 and mesh 120). For smaller grit sizes (#80), low surface roughness was achieved with impingement angles between 30˚ to 90˚. While for the larger grit sizes (#120), there was an increase in the roughness values at an impingement angle of 60˚.

Fowler et al (2009) have carried out AWJPM in titanium alloy (Ti6Al4V) to study the effects of different abrasive particle (white and brown aluminium oxide, garnet, glass beads and steel shots) shape and hardness . They have observed that the ratio between the hardness of the workpiece and the abrasive particle is more significant than that of abrasive particle shape. They have also observed that increase in the material removal rate and surface roughness with the increase in the abrasive particle hardness. They have observed that among the different input process parameter, traverse rate is found to be more significant for material removal rate for different abrasives. They have also found that shape factor and particle hardness have no significant effect on the surface waviness.

Kong et al (2011) have carried out AWJPM in Ni-Ti shape memory alloy and observed that the AWJPM is having a better control over depth of cut than that of the plain water jet pocket milling (PWJPM) process. They have found that the surface generated by PWJPM is relatively smooth compare to AWJPM, except the existence of some locally deformed and pulled-out spots (e.g. craters) during the first milling pass. However, with the increase in the number of pocket milling passes (3 passes) more craters with higher surface roughness were observed. They have also observed larger craters with higher surface roughness and with lower erosion resistance with inclination of the nozzle at 75˚. They have also found that the material removal occurs predominantly by micro-abrasion mechanism, which involves grooving and ploughing.

From the literarture review, it is observed that few works are carried out in AWJPM on titanum alloy. This paper analyses the effect AWJPM process parameters such as waterjet pressure, step-over, traverse rate and abrasive mass flow rate on the depth of cut and surface roughness (R_a) on titanium during AWJPM.

3. EXPERIMENTAL SETUP AND PROCEDURE

Precision WaterJet Machining Center (Model: 2626) manufactured by M/s OMAX Corporation, USA is used for this work. The equipment details are given in Table 1.

Figure 2. Photograph of the AWJM setup

AWJPM is carried out in Titanium (CuZn40) of thickness 6 mm. Titanium was chosen as the workpiece as it is used for many industrial applications. To measure the hardness of the workpiece, the Vicker's hardness tester is used at 0.5 Kg load for 10 seconds at three different locations. The average value of hardness is found to be 128.4 HV. Garnet abrasive of grit size of mesh #85 is used for the experimention. The four input parameters that were varied at three levels (low, medium and high) are waterjet pressure, step over distance, traverse rate and abrasive mass flow rate (Table 2). These parameters are found to be influncing significantly in AWJPM (3-6). The ranges of these parameters are selected based on the trail runs.

Table 1. AWJM details

Machine used	OMAX 2626 Precision Jet Machining Center
Power	22kW, 50 Hz
Min Waterjet Pressure	138 MPa
Max Waterjet Pressure	413 MPa
CNC Work Table size	1168 mm x 787 mm
Work Envelope	X-Y cutting travel of 737 mm x 660 mm
Focusing Nozzle diameter	0.76 mm
Orifice diameter	0.35 mm

Table 2. Variable process parameters at different levels

S. No.	Variable Process Parameters	Levels		
		Low	Medium	High
1	Waterjet Pressure (MPa)	138	155	172
2	Step Over (mm)	0.2	0.3	0.4
3	Traverse Rate (mm/min)	1500	2000	2500
4	Abrasive Mass Flow Rate (kg/min)	0.22	0.32	0.42

Raster path is chosen while cutting the workpiece materials (Figure 10). The raster path is a path in which the abrasive waterjet moves in straight cut. However, during at the ends of each pass, the jet makes a 90˚ turn, after which it moves linearly as per the pre-specified step over distance. Thereafter, it takes another 90˚ turn and then proceeds for the next straight cut. This step is repeated to cover the entire area specified by the user.

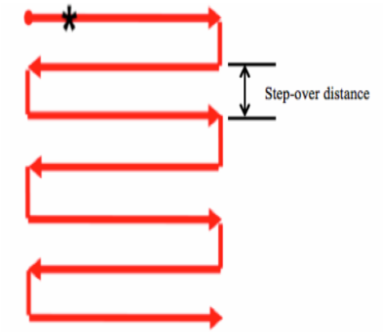

Figure 3. Flow pattern of raster path

The experiments were designed using L_9 orthogonal array (OA). The responses are then measured and ANOVA analysis is performed to determine the significant parameters. The experimental results are given in Table 3.

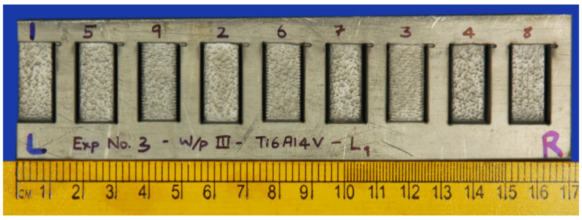

Figure 4. AWJPM of Titanium alloy as per L_9 OA

The depth of cut is measured using TESA IP67 Digital Vernier Calliper with least count of 0.01mm, while the surface roughness (R_a) is measured using a Mahr Marsurf make contact type surface roughness tester with a traverse length of 5.6 mm, cut-off length of 0.8 mm and using a Phase corrected Gaussian filter.

4. RESULTS AND DISCUSSIONS

The depth of cut and surface roughness (R_a) values obtained are given in Table 3. ANOVA TM software is used for statistical analysis. The input parameters which contribute significantly have been determined and the response graphs are plotted.

4.1 Analysis of depth of cut

ANOVA table (Table 4) indicates that the step-over and traverse rate are significant process parameters (at 90% confidence level). Abrasive flow rate and pressure are found to be insignificant. Even though the Abrasive flow rate and waterjet pressure are not siguinificant, the trend can be observed from the response graphs (Figure 12).

Response graphs in Figure 12 indicate that high pressure, low step-over distance, low traverse rate and high abrasive flow rate results in higher depth of cut. The follwing are observed from the response graphs in Figure 12; as the depth of cut increases with increase in the waterjet pressure. This indicates that as the waterjet pressure increases, the kinetic energy of jet and abrasive particles also increases thus resulting in a higher depth of cut.

The depth of cut decreases as step-over decreases. This may be due to the increase in number of waterjet passes overlapping per unit area on the workpiece surface due to raster path. Depth of cut decreases with increase in traverse rate. This is due to the faster movement of the waterjet over the workpiece. Higher abrasive flow rate results in higher depth of cut. This may be due to the interaction of a larger number of abrasive particles on the workpiece surface, which are also similarly observed by [7].

Table 3. Experimental results

S. No	Input Process Parameters				Output Process Parameters	
	Pressure (MPa)	Step Over (mm)	Traverse Rate (mm/min)	Abrasive Flow Rate (kg/min)	Surface Roughness (µm)	Depth of Cut (mm)
1	138	0.2	1500	0.22	3.53	1.9
2	138	0.3	2000	0.32	4.86	0.93
3	138	0.4	2500	0.42	5.04	0.29
4	155	0.2	2000	0.42	4.2	1.85
5	155	0.3	2500	0.22	6.35	0.84
6	155	0.4	1500	0.32	5	1.25
7	172	0.2	2500	0.32	6.68	1.87
8	172	0.3	1500	0.42	3.85	2.28
9	172	0.4	2000	0.22	10.1	0.86

Table 4. ANOVA Table

Source	Pool	DF	S	V	F	S'	ρ
P	-	2	0.60	0.30	5.35	0.49	13.99
SO*	-	2	1.73	0.87	15.41	1.62	46.34
TR*	-	2	1.05	0.52	9.34	0.94	26.81
AFR	Y	2	0.11	0.06	-	-	-
(e)	-	2	0.11	0.06	-	0.45	12.86
Total	-	8	3.49	0.44	-	-	-

P - Waterjet pressure, SO - Step over, TR - Traverse rate, AFR - Abrasive mass flow rate, (e) - Error, Y - Pooled variable DF - Degrees of freedom, S - Sum of squares, V - Variance, F - F ratio, S' - Pure sum of squares, ρ - Percentage contribution (%)
*** - Significant Parameter**

Table 5. ANOVA Table for Surface Roughness

Source	Pool	DF	S	V	F	S'	ρ
P	-	2	9.13	4.57	1.40	2.59	7.98
SO	Y	2	6.54	3.27	-	-	-
TR	-	2	8.83	4.42	1.35	2.29	7.06
AFR	-	2	7.93	3.97	1.21	1.39	4.28
(e)	-	2	6.54	3.27	-	26.17	80.68
Total	-	8	32.43	4.05	-	-	-

P - Waterjet pressure, SO - Step over, TR - Traverse rate, AFR - Abrasive mass flow rate, (e) - Error, Y - Pooled variable DF - Degrees of freedom, S - Sum of squares, V - Variance, F - F ratio, S' - Pure sum of squares, ρ - Percentage contribution (%)
*** - Significant Parameter**

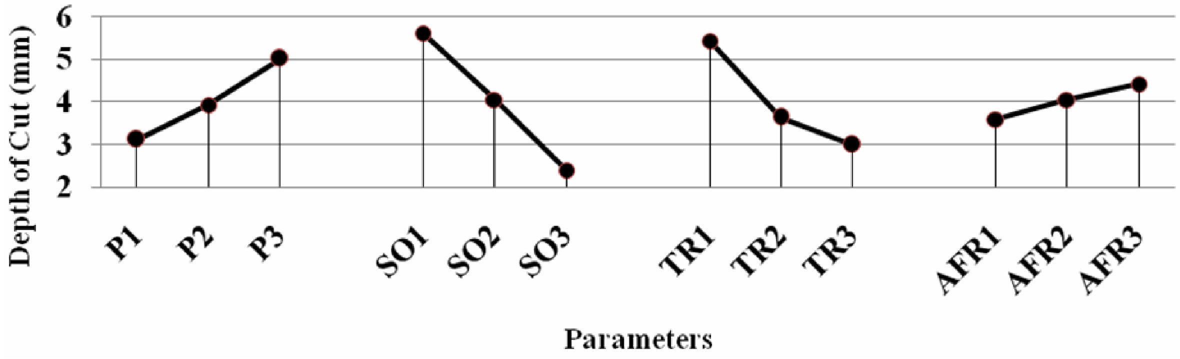

Figure 5. Mean Responses - Parameters Vs Depth of cut (mm)

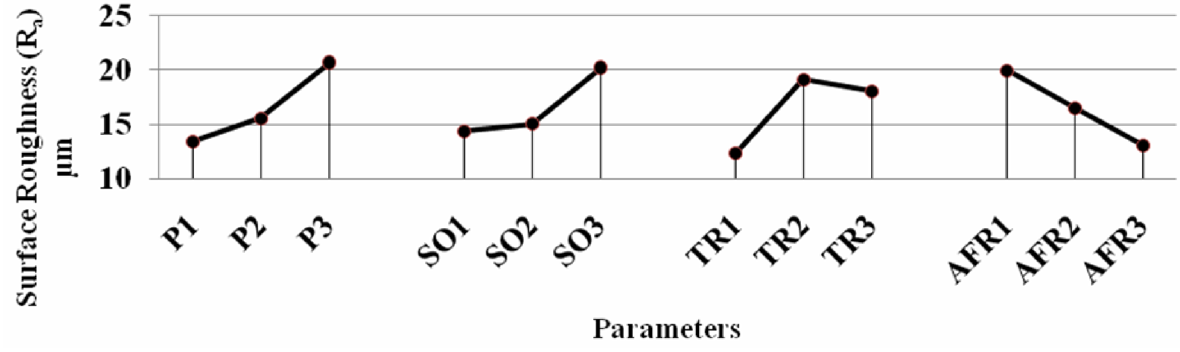

Figure 6. Mean Responses - Parameters Vs Surface Roughness (R_a) µm

4.2 Analysis of surface roughness (R_a)

While ANOVA analysis successfully yielded the significant parameters for the resultant depth of cut, the same is not found for surface roughness (R_a). From Table 5, the significance of individual parameters could not be determined using the L_9 Orthogonal Array Design of Experiments approach. This indicates that higher order of experimentation is necessary to determine the significant parameters. However, from the response graphs (Figure 13), it is observed that lower R_a values are obtained with low waterjet pressure, low step-over, low traverse rate and high abrasive flow rate. These levels are required for achieving lower R_a.

5. CONCLUSION

This work aims to determine the significant input parameters in AWJPM of titanium for achieving higher depth of cut and lower surface roughness (R_a). ANOVA analysis is carried out to identify the significant process parameters and their corresponding response graphs were plotted.

The step-over and the traverse rate play the most significant role in achieving higher depth of cut. The depth of cut reacts inversely with step-over and traverse rate. However, it varies directly with waterjet pressure. This indicates that high step over and high traverse rate, lead to lower depth of cut. In the case surface roughness (R_a), it is observed that a higher order of experimentation is necessary to understand the effects of input parameters. This leaves a lot of scope for future study.

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ЕКСПЕРИМЕНТАЛНА ИСТРАЖИВАЊА ГЛОДАЊА ЖЉЕБА ОД ЛЕГУРЕ ТИТАНИЈУМА ПРИМЕНОМ ОБРАДЕ АБРАЗИВНИМ ВОДЕНИМ МЛАЗОМ

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Обрада абразивним воденим млазом је један од најраспрострањенијих неконвенционалиних процеса обраде материјала тешких за обраду. Поред обраде резањем, користи се за и за обраду стругањем, нарезивање навоја, израду жљебова, глодање, итд. У овом раду подробно су приказана експериментална истраживања обраде титанијума (Ti6Al4V) абразив–ним воденим млазом применом гранатног абразива. Вршена су испитивања утицаја притиска воденог млаза, размака између путања алата, брзина путање алата и брзине протока абразивне масе на коначне

вредности дубине резања и рапавости површине. План експеримената је направљен помоћу програмског пакета L9 Orthogonal Array док је ANOVA анализа варијансе била од помоћи код одређивања значаја процеса. ANOVA анализа дубине резања је показала да су размак између путања алата и брзина путање алата два најважније параметра процеса. Међутим, ANOVA анализа рапавости површине није дала убедљиве резултате и параметри од значаја за процес обраде нису могли бити одређени.